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Environmental assessment of woven hemp fibre reinforced epoxy composites and potential applications in aerospace and electric scooter industries

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A R T I C L E I N F O

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A B S T R A C T

This paper aims to present a hemp-based natural fibres composite value chain that could be implemented in biocomposite structures and replace synthetic fibres. Life cycle assessment (LCA) allows the assessment of the environmental footprint of the hemp fibre reinforcement value chain. This general case is complemented with two hemp fibre reinforcement applications, i.e. (1) a hemp fibre reinforced epoxy-based aircraft dashboard panel and (2) a hemp fibre reinforced epoxy-based biomonocoque for an electric scooter. LCA is also used to assess the environmental footprint of the application cases. All the hemp fibre-based value chain applications shown here demonstrate a lower environmental footprint than the fossil-based reinforcement value chain, particularly regarding the global warming potential, among other impact categories except for the case where the specific tensile strength was used as the functional unit for comparison. Impact categories related to agricultural activities, such as the eutrophication potential, land use, and freshwater consumption, are higher for the hemp-based value chains than for conventional synthetic fibre-based solutions. This study shows how conventional synthetic fibre products have the potential to be replaced by hemp-based natural fibre solutions depending on the required applications, which could lower the environmental footprint and help contribute to the ongoing climate mitigation efforts.

1. Introduction

In today's ever-evolving world, conventional composites are often used for the production of components and services in various sectors, ranging from transportation to medical and general consumer goods and appliances [1,2]. The current demands for consumer goods, services, and products are on a constant increase proportional to the current growth rate of the World's population. This subsequently also increases the global demand and production of composites [3]. The compound annual growth rate (CAGR) of the polymer composite market is set to increase between 6,6 % and 12.4 % during the forecast period of 2015–2026 [3,4]. Additionally, the CAGR of the global composite market for the aerospace sector is estimated to be 32 billion USD in 2021, with a CAGR of approximately 9 % in the period of 2016–2021 [4,5]. By definition, a polymer composite is generally made of two materials, namely the (1) polymer matrix and the (2) synthetic fibre reinforcement [6]. The combination of the two materials synergistically improves the mechanical properties of the composite; the latter provides superior mechanical properties of conventional single-phase materials. However, both the polymer matrix and the synthetic fibre

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reinforcements are often produced and derived from fossil fuels, which consequently leads to possible large stresses to the environment, especially in terms of greenhouse gas emissions when they are incinerated [7,8]. The current climate change crisis catalyzed by emissions of greenhouse gases from fossil fuel combustion, as well as the currently limited supply of fossil fuels, drive ongoing international efforts to transition from current fossil-based conventional composites to bio-based ones [9]. This, in turn, can lead the world to become less reliant on fossil fuels, thereby, ameliorating the overall effects of climate change. This topic can directly be linked with the Sustainable Development Goals (SDGs) of the United Nations. Particularly, this transition can directly fulfill and contribute to the 12th SDG on responsible consumption and production in a more circular manner. Subsequently, this can help improve the other SDGs such as SDGs 13 to 15 which cover environmental aspects including climate action, life below water, and life on land.

Bio-composites are defined as materials where at least one of the two constituents, namely the matrix or the fibre reinforcement, is bio-based. In other words, bio-composites could potentially consist of the (1) (bio-) polymer matrix or the (2) natural fibre reinforcements (NFR), or ideally both [10,11]. The replacement of synthetic fibre reinforcements with natural fibre ones is gaining attraction in composite research, as it is believed that natural fibre-reinforced composites (NFRCs) often lead to advantages over their conventional counterparts. Natural fibre-reinforced composites can be also more environmentally friendly, less energy-intensive in production, biodegradable, and potentially cheaper and lighter than their synthetic fibre-reinforced versions, while still providing a relatively comparable mechanical performance [7,10] Despite their relatively good mechanical characteristics and their benefits in terms of environmental performance, NFR have also disadvantages like high moisture absorption, poor wettability, and even lower compatibility with certain polymer matrices [12]. Further building on this point, it can often be misleading to pretend that NFRs have superior environmental performance per se. This is due to the fact that the mechanical properties of the NFR cannot often be directly compared with those of conventional synthetic fibres since more NFR are required to achieve the equivalent mechanical properties of synthetic fibres. In addition to this, the expected life of NFR is less than those of synthetic fibres [11]. Consequently, higher demands for volumes of NFR to reach equivalent mechanical properties can potentially add strain to the biosphere, even if the global warming potential (GWP), cumulative energy demands (CED), or toxicity are lower than those exhibited by synthetic fibres production [9,13,14]. The agricultural activities needed to satisfy the demands of increased volumes of NFRs often involve higher environmental impacts on land use, eutrophication, and freshwater [9,13,14] Nonetheless, even with these drawbacks, the efforts in the transition from synthetic fibres to natural fibre reinforcements are certainly warranted.

Different life cycle assessment (LCA) studies have demonstrated the ecological benefits of replacing synthetic fibres with natural reinforcements to produce composites, especially in terms of global warming potential (GWP) and cumulative energy demand (CED). LCA will be defined in Section 2.1. Based on the study of Joshi et al. [14], the demand for nonrenewable energy for the production of glass fibre mat is equivalent to 54.7 $\frac{MJ}{kg}$; this value decreases to 9.55 MJ per kg in the cases of flax fibres mat. Lower energy requirements lead to lower emissions, as well as to the reduction of costs associated with energy generation. Weiss et al. [15] reviewed over 60 bio-based materials, including bio-composites, that were described in 40 LCA studies. The review concluded that the production of one tonne of bio-based materials may help reduce the primary energy demand by up to 55 GJ when compared to the production of one tonne of conventional fossil-based materials. Additionally, the review also reported a reduction between 2 and 4 tonns of kg CO_2 eq. to produce one tonne of bio-based materials, in comparison to the production of one tonne of fossil-based ones. The review study of Malviya [16] has also demonstrated the environmental benefits of natural fibre composites as opposed to their conventional synthetic fibre counterparts in terms of reduction of greenhouse gas emissions, which in turn decrease the global warming potential (GWP). The main explanation for this reduction can be attributed to the use of natural fibres, which are considered biomass and lead to the temporary sequestration of the atmospheric carbon concentration during their growth and use cycles. In addition to this, the use of biomass also does not release stored carbon content until end-of-life, as it would have been in the case of the polymerization of the derivatives of fossil fuels for synthetic fibres. To this end, different LCA studies have iterated and highlighted the potential for natural fibre reinforcements to help to reduce the impacts of climate change when compared to synthetic fibre reinforcements.

Within the scope of this study, the focus is on hemp fibres as natural fibre reinforcements in bio-composites. Hemp fibre-reinforced composites can perform mechanically well in comparison to base polymer matrix or synthetic fibers-reinforced composites. For instance, the review study of Mahir et al. [11] reported an increase of approximately 54 % in terms of flexural modulus for hemp fibre-reinforced vinyl ester composites (20 wt% fibre content) when compared to the base vinyl ester polymer. The review of Shahzad et al. [17] described a set of comparable mechanical properties, (tensile modulus, flexural strength, flexural modulus, and impact strength) for hemp fibre-reinforced polypropylene composites with a weight percentage fibre fraction between 30 % and 64 %, when compared to glass fibre reinforced polypropylene composites (the latter with glass fibre volume fraction of 22 %). In the most optimal fibre weight fraction considered in that study, the tensile modulus was 10.2 GPa for the long hemp fibre reinforced composites, as opposed to 6.2 GPa for those reinforced by glass fibres. The flexural strength of the hemp composite was 85 MPa, as opposed to 60 MPa of the glass fibres; the flexural modulus and impact strength of the hemp-based composite was 4.7 GPa and 53 $\frac{kJ}{m^2}$ respectively, against the 4.4 GPa and 54,12 $\frac{kJ}{m^2}$ of the glass fibre counterpart. Furthermore, Sala et al. [18] have demonstrated that when monotonic and creep performances are considered, sandwich beams based on woven hemp composite skins, balsa wood, and paper honeycomb cores appear to perform better than typical glass-fiber-reinforced composite sandwich structures. In addition to the comparable mechanical properties of hemp fibre reinforced composites versus those of conventional synthetic fibre reinforced materials like glass fibres, the ecological footprint for the production of the hemp fibres reinforced composites is smaller, in particular for the cases of the global warming potential (GWP) and energy requirements. To support this, the study by Wotzel et al. [19] investigated the environmental impacts and the energy requirements to produce side panels of an A3 Audi vehicle made of either ABS copolymer or hemp-epoxy composite. The study demonstrated that the total energy requirements for hemp-epoxy composite production were 73 $\frac{MJ}{panel}$, in comparison to the 132 $\frac{MJ}{panel}$ of the ABS copolymer case. Additionally, the carbon dioxide emission was 4.19 kg CO_2 for the production of the hemp-epoxy composite side panel, against the 4.97 kg CO_2 of the ABS copolymer counterpart. Given the promising results provided by these studies, hemp fibre reinforcements are of strong interest for implementations in natural fibre-reinforced composites (NFRCs) and replace conventional fossil-based structures. At the moment hemp fibre-reinforced composites are being used, prototyped, and produced for automotive, aviation, consumer products, transport and shipping, construction, and furniture industries.

To this end, this study aims to assess the environmental performances of continuous hemp fibre reinforcements in comparison to conventional fossil-based glass fibre ones. The assessment is made for a complete range of environmental indicators. In addition to this, the study also aims at demonstrating the environmental benefits and tradeoffs of using hemp fibre reinforcements in two real-world case studies, namely the production of an aircraft cockpit dashboard panel and the manufacturing of a bio-monocoque for an electric scooter related to the 2-wheels vehicle industries. Both case studies are at the demonstrator level, hence, no mass production is involved and the results only pertain to lab-scale developments. The results and the outcome of these case studies emphasize the importance of the transition and replacement of fossil-derived synthetic fibre reinforcements with natural fibres. To achieve these objectives, section 2 describes the LCA methodology that was employed within this study as a tool to quantify the environmental impacts of the hemp reinforcement value chain, as well as the production of the two demonstrators. In addition to this, section 2 provides the background description as well as information about the inventory of the hemp value chain and the production processes of the two demonstrators in detail. The results of the environmental impacts are presented in section 3, along with an extensive discussion based on these results.

2. Methodology

2.1. Description of methodology (life cycle assessment)

The environmental performance of the processes and materials produced in this study was evaluated using the LCA framework. The assessment was conducted following the ISO standards on LCA (ISO 14040, 2006; ISO 14044, 2006) [20] and the International Reference Life Cycle Data System (ILCD) Handbook published by the European Commission's Joint Research Centre [21].

The framework is a four-phase process that includes: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation of results. In the first stage, the goal and scope of the study must be defined. Critical components such as system boundaries, functional units, reference flow, and allocation rules are specified and described during the goal and scope definition phase. Next, the life cycle inventory is set up. This phase aims at building and analyzing the mass and energy balance of the products and processes developed in the study. The compilation and quantification of relevant inputs and outputs for the system under investigation throughout its life cycle with respect to the predetermined reference flow is the focus of this second phase. The inputs can include but are not limited to, materials and energy resources. The outputs of the procedures also comprise the intermediate and end products and waste streams. Specific to this study, foreground data was collected by a questionnaire in the form of an Excel file and sent to the different actors throughout the hemp fibre reinforcement value chain. To further elucidate, the data, such as the mass and energy flows required for the life cycle inventory phase, was collected by involving the different stakeholders in the project. Therefore, this study used real-life experimental and field data for hemp preform production, bio composite production for aerospace, and scooter production in the LCA.

The Life Cycle Impact Assessment is the third phase of an LCA assessment (LCIA). The environmental implications of the product system throughout its life cycle are deduced from the inventory in this phase. The LCA modeling was done following the goals and scope of the study, utilizing data from the life cycle inventory that had been gathered and assessed in the second step (LCI). Environmental impact categories are classifications that indicate relevant environmental concerns in the impact assessment. Finally, the last phase of an LCA is the interpretation of the results. This is when all of the previous phases' results are combined and examined.

2.2. Systems description

Within this section, the description of the hemp fibre reinforcement value chain as well as the two application case studies are given in detail. The functional unit, goal and scope, system boundary from field to factory gate, reference flows, allocation method, and the software used are mentioned in 2.1.1 for the hemp value chain, 2.2.2 for the aircraft dashboard panel demonstrator case study and 2.2.3 for the bioscooter demonstrator case study. For each sub-section, the detailed life cycle inventory data are presented and discussed.

2.2.1. Hemp value chain

The hemp reinforcements were produced according to the value chain developed within the EU-Horizon 2020 SSUCHY project. The project investigated innovative pathways to produce fully bio-based composite constituents (fibre reinforcement and resin matrix) in order to construct novel biocomposites for high-value-added applications ranging from applications in the aerospace industry to the transport industry to the auditory electronics industry. The value chain follows the life cycle inventory displayed below in Table 1. To elaborate on the inventory, firstly, the hemp plants were cultivated and harvested [22] from the fields. The cultivation and harvesting conditions were extrapolated from data available for the hemp plant [23] field-retted cultivation and harvesting process [15] available on the Ecoinvent 3.3 database and open literature [22–25]. The hemp fibres were allocated based on 7.9 % [26] of the total yields of the hemp harvest, based on the data provided by the partner Ecole Nationale d'Ingénieurs de Tarbes. To elucidate, this percentage represents the amount of environmental impacts allocated to the production of hemp fibres from the hemp cultivation processes. This yield was obtained with non-optimized processing which means that this value can be improved in the future. The hemp plants were then transported and the fibres were extracted with the energy requirements according to the works of Dissayanake et al. (2009) [26]. For transportation, the site of the fibre extraction and preform production was assumed to be within a 100 km radius of the cultivation and harvesting site based on data collected within the project. The process of fibre extraction includes the steps of cutting the hemp plants with saw blades, scutching, drawing/doubling process, yarn rovings formation, and weaving. The plain weave fabric has an areal density of approximately 278 ± 8 g/ m^2. Subsequently, the extracted long hemp fibres underwent a chemical pretreatment and weaving process in order to result in hemp preforms as indicated in Table 1. The inventory in Table 1 is presented for the mass unit of 0.4 kg hemp preform. Table 2 summarises the mechanical properties, particularly the specific E-modulus and tensile strength of the hemp, glass, and carbon fibre reinforcements. The table also included the calculation of the amount of mass required to achieve (1) equivalent specific E-modulus and (2) tensile strength. In order to hold the specific E-modulus and tensile strength the same for all three materials, the mass of the preform was changed based on the required aerial density reported during the data collection.

The specific tensile strength and specific Young's modulus were calculated based on equations (1) and (2), respectively:

$$\text{Specific Tensile strength}\left(\frac{\text{GPa.dm}^3}{\text{kg}}\right)=\frac{\text{Tensile Strength (GPa)}}{Density\left(\frac{g}{cm3}\right)} \quad (1)$$

$$\text{Specific Young's Modules}\left(\frac{\text{GPa.dm}^3}{\text{kg}}\right)=\frac{\text{Young's Modules (GPa)}}{Density\left(\frac{g}{cm3}\right)} \quad (2)$$

Following this, the same specific Young's modulus values were applied to both natural and synthetic fibers for an equal volume, and the amount of material required to attain the same specific tensile strength/ specific Young's modulus was calculated.

These two mechanical properties are henceforth the functional unit of this LCA study on natural fibre reinforcements. The environmental impacts are then calculated and extrapolated to the determined mass to fulfil the two functional units. These mass units are the reference flows. An assumption was made that the manufacturing of the preform is located in the same processing location as the fibre extraction and, hence, there was no need for further transportation. Within the inventory and LCA model, the chemical pretreatment inputs include sodium hydroxide, sodium percarbonate, detergent, and water. The

Table 1
Life cycle inventory of the hemp long fibre preform production.

Long Hemp Fibre Preform Production (per 0.4 kg)							
	Quantity per 1 m^2	Unit	Data source	Output	Quantity per 1 m^2	Unit	Data source
Hemp Long Fibre, Torn (8 % H_2O Content)	0.403	kg	Experimental data	Woven Hemp Long Fibre Preform (1 m^2)	0.4	kg	Experimental data
Sodium carbonate, powder	0.000069	kg	Ecoinvent 3.3				
Sodium Hydroxide	0.000345	kg	Ecoinvent 3.3				
Electricity from natural gas (IT)	0.69	kWh	Ecoinvent 3.3				
Tap water	0.00172	kg	Ecoinvent 3.3				
Electricity for weaving, bast fibre	2.24	kWh	Ecoinvent 3.3				

Table 2
Mechanical properties of the natural fibre and synthetic fibre reinforcements and the calculated amount of mass required to achieve equivalent mechanical properties [15].

Fibre	Density $(\frac{g}{cm^3})$	Calculated Mass Required to Achieve Equivalent Specific Young's Modules			Calculated Mass Required to Achieve Equivalent Specific Tensile Strength		
		Young's Modulus (GPa)	Specific Young's Modules $\left(\frac{GPa.dm^3}{kg}\right)$	Amount in kg to achieve equivalent Specific Bending Stiffness	Tensile Strength (GPa)	Specific Tensile strength $\left(\frac{GPa.dm^3}{kg}\right)$	Amount in kg to achieve equivalent Tensile strength
Hemp	1.48	29.45	19.899	0.050	0.735	0.496	2.01
Glass	2.5	56	22.40	0.044	2.200	0.880	1.13
Carbon	1.875	235	125.33	0.007	4.000	2.133	0.47

detergent was modelled as the alkyl benzene sulfonates as an alternate input on the Ecoinvent database. The LCA provided a comparison with glass fibre production. The process for glass fibre production is taken from the Ecoinvent 3.3 database. Data processing and system modelling were carried out using the LCA software GaBi (8.7.0.18). The Ecoinvent 3.3 database was consulted for the LCA model, and the ReCiPe 2016 was the life cycle impact assessment methodology chosen for the quantification of the environmental performances. The glass fibre reinforcement [26]has an areal density of approximately 260 g/ m^2 and 80 g/ m^2 for the carbon fibre. The results of the LCA are provided in section 3. Finally, the produced hemp preforms became the fibre reinforcements for the two demonstrator cases described in sections 2.1.2 and 2.1.3 for the aircraft dashboard panel and the bio-monocoque for an electric scooter respectively.

2.2.2. Case study application 1: aircraft dashboard panel demonstrator

The purpose of this first demonstrator case was to create a set of interior designs (CAD/CAE) and a panel display for a fully – electric 10 PAX twin-engine aircraft with a Maximum Take-Off Weight (MTOW) of 2.78 kg (EASA CS 23). The twin-engine electric aircraft was designed using the SCYLAX concept developed by EADCO and PC-AERO. This demonstration was built to assist designers in the design of airplane components such as dashboards, cabin interiors, and sound and vibration-proofing panels. The panel was created using an autoclave/ vacuum-bagging method on a custom-made curved plate/mould fabricated at the University of Bristol. The manufactured panel is a sandwich panel with a core material composed of Divinycell foam and hemp-based composite skins. The composite skins are made up of woven hemp fabric and commercially available epoxy resin films.

The LCA study on this first application case covers the whole manufacturing process of the SSUCHY biocomposite aircraft dashboard panel. Specifically, this study compares the environmental performance of the aircraft dashboard panel's production phase to that of a conventional panel, namely an autoclaved carbon fiber-reinforced epoxy. The hemp-based biocomposite panel weighed 1.53 kg, hence, this is the reference flow value. As a result, inventories are computed and measured with respect to this reference flow. The inventory is summarized in Table 3 to display the mass and energy flow for the production processes.

The mass and energy inventory was generated for one aircraft dashboard composite. A flowchart depicting the steps involved in the bio-composite cockpit dashboard is illustrated in Fig. 1.

Based on the Ecoinvent 3.3 database, an inventory was created for the manufacturing of 0.792 kg of autoclaved carbon fiber-reinforced epoxy composite for the benchmark comparison. Data processing and system modelling was carried out using the LCA software GaBi (8.7.0.18). The Ecoinvent 3.3 database was consulted for the LCA model, and the ReCiPe 2016 midpoint was the life cycle impact assessment methodology chosen for the quantification of the environmental performances. The assessment in this study is reflective of European-scale production. Background data are gathered for the EU-28. Where the EU-28 dataset is not accessible, a dataset with the global geographical average is used instead.

According to the data provided by the project partner, the plies' cutting preparation was done by hand. Polyvinyl chloride foam (PVC) foam is assumed to be like the Divinycell F40 PVC Foam Core and the Divinycell F130 PVC Foam Core. The tacky tape is assumed to be a sealing tape as this was the only available tape on the Ecoinvent 3.3 database. Furthermore, according to the investigations of Dissanayake et al. [26] [][26][]and Hayo et al. [23], the energy demands for hemp reinforcement production were estimated to be similar to those for flax preform production, also based on consulting the project partner. The mould can be used several times during the manufacturing process. According to the data given by the project partner, the mass balance and energy consumption profile are reported in Table 3. The autoclaved, carbon fiber reinforced epoxy composite benchmark was designed using the market's Ecoinvent 3.3 process for carbon fiber reinforced plastic, with a reported mass of 0.792 kg. The wastes obtained throughout the production process are taken into account in the LCA as incinerated with energy recovery. The inert waste is landfilled.

2.2.3. Case study application 2: scooter monocoque demonstrator

This LCA study on the second application demonstrator case includes the production phase of a bio-monocoque for a scooter. The analysis compares the environmental performance of the production of the bio-monocoque for an electric scooter against the conventional steel frame. A bio-scooter design was created using a new AkzoNobel polyester technology [27]. The scooter design was changed using CAD/CAE procedures and hot-press moulding preforms were used in the production. The functional unit for this analysis is equivalent to one scooter

Table 3
Inventory for the production of 1.53 kg of hemp fibre-reinforced epoxy-based aircraft dashboard composite panel.

Cutting using scissors or knife				
Input	Amount	Unit	Remark	Data source
Epoxy Resin Film	4.00	kg		Ecoinvent 3.3
Hemp Satin	3.44	kg		Ecoinvent 3.3
Cutting			By hand	Experimental data
Output	**Amount**	**Unit**		**Data source**
Epoxy Resin Film	3.89	kg		Intermediate product
Hemp Satin	2.69	kg		Intermediate product
Stacking of the cut plies in a tool plate (vacuum bag)				
Input	**Amount**	**Unit**		**Data source**
Epoxy Resin Film	3.89	kg		Intermediate product
Hemp Satin	2.69	kg		Intermediate product
Divinycell F40 PVC Foam Core	0.13	kg		Ecoinvent 3.3
Divinycell F130 PVC Foam Core	0.42	kg	Reusable	Experimental data
Mould release film	0.02	kg		Ecoinvent 3.3
Breather	0.10	kg	Fabric	Ecoinvent 3.3
Vacuum bag	0.15	kg		Ecoinvent 3.3
Cork	0.60	kg	Cork slab	Ecoinvent 3.3
Tacky tape	0.50	kg		Ecoinvent 3.3
Mould plate	30.00	kg	Reusable	Experimental data
Output	**Amount**	**Unit**		**Data source**
Composite Plate	4.16	kg		Intermediate product
Mould plate	30.00	kg	Reusable	Experimental data
Curing at autoclave				
Input	**Amount**	**Unit**		**Data source**
Composite Plate	4.16	kg		Intermediate product
Autoclave	13.00	kWh	Curing	Ecoinvent v3.3
Output	**Amount**	**Unit**		**Data source**
Cured Composite Plate	4.16	kg		Intermediate product
Demoulding				
Input	**Amount**	**Unit**		**Data source**
Acetone	0.50	kg	Tool plate preparation (cleaning)	Intermediate product
Mould plate	30.00	kg	Reusable	Experimental data
Cured Composite Plate	4.16	kg		Ecoinvent v3.3
Output	**Amount**	**Unit**		**Data source**
Mould plate	30.00	kg	Reusable	Experimental data
Cured Composite Plate	4.16	kg		Intermediate product
Piece or specimen laser cutting				
Input	**Amount**	**Unit**		**Data source**
Cured Composite Plate	4.16	kg		Intermediate product
Laser Cutting	0.40	kWh		Ecoinvent v3.3
Output	**Amount**	**Unit**		**Data source**
Net Dashboard Panel	1.53	kg		Product

body frame. The redesigned bio-monocoque weighed 14.3 kg which serves in this analysis as the reference flow. As a result, the inventory was extrapolated and measured based on this value. The inventory is reported in Table 4 as the mass and energy inventory. The benchmark was a steel body frame based on an Aprilia SR50 with a mass of 23.6 kg. Of the total mass of 23.6 kg, 14.6 kg was attributed to the steel frame weight and 9 kg to the acrylonitrile butadiene styrene bodywork weight (ABS). A flowsheet depicting the steps involved in the manufacture of bio-composites can be seen in Fig. 2 (see Table 5).

Data processing and system modelling was carried out using the LCA software GaBi (8.7.0.18). The Ecoinvent 3.3 database was consulted for the LCA model, and the ReCiPe 2016 was the life cycle impact assessment methodology chosen for the quantification of the environmental performances.

The mass balance and energy consumption profile were calculated using information from the project partner to obtain the full inventory of the bio-monocoque. As for the benchmark, empirical measurements and product datasheets from the producer were consulted in order to

Table 4
Inventory for the production of the bio-monocoque for an electric scooter.

Cutting the fibre			
Input	Amount	Unit	Data source
Hemp reinforcement	4.900	kg	Ecoinvent 3.3
Cork core	0.790	kg	Ecoinvent 3.3
Electricity Grid Mix	0.366	kWh	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Cut hemp	3.675	kg	Intermediate Product
Cut cork	0.713	kg	Intermediate Product
Cork waste	0.120	kg	Waste
Hemp waste	1.225	kg	Waste
Drying of the fibre			
Input	**Amount**	**Unit**	**Data source**
Cut hemp	3.680	kg	Intermediate Product
Cut cork	0.713	kg	Intermediate Product
Electricity Grid Mix	8.360	kWh	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Dry skins	4.390	kg	Intermediate Product
Stacking and preparation			
Input	**Amount**	**Unit**	**Data source**
Dry skins	4.388	kg	Intermediate Product
Epoxy-based gel coat	1.430	kg	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Gel coated skins	5.675	kg	Intermediate Product
Epoxy Gelcoat waste	0.143	kg	Waste
Vacuum and curing			
Input	**Amount**	**Unit**	**Data source**
Gel coated skins	5.675	kg	Intermediate Product
Epoxy Resin/Bis-Guaiacol Resin	7.700	kg	Ecoinvent 3.3
Hardener	1.690	kg	Ecoinvent 3.3
VARI Equipment	0.200	kg	Ecoinvent 3.3
Electricity Grid Mix	1.960	kWh	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Bio-monocoque	14.100	kg	Intermediate Product
VARI Waste	0.200	kg	Waste
Finishing			
Input	**Amount**	**Unit**	**Data source**
Bio-monocoque	14.100	kg	Intermediate Product
Abrasive sand	3.160	kg	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Finished Bio-monocoque	14.100	kg	Product
Inert waste	3.160	kg	Waste

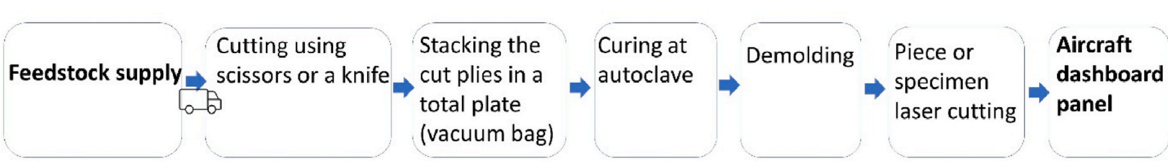

Fig. 1. Flowsheet of the aircraft dashboard panel production.

Table 5
Inventory for the production of the steel scooter frame with ABS bodyworks benchmark.

Body production			
Input	Amount	Unit	Data source
Phenol	6.63	g	Ecoinvent 3.3
Anhydrite (CaSO4) (EN15804 A1-A3)	92.2	g	Ecoinvent 3.3
Crude oil mix	1010	kg	Ecoinvent 3.3
Electricity from hydropower	216	MJ	Ecoinvent 3.3
Electricity grid mix	6390	MJ	Ecoinvent 3.3
Natural gas mix	2.67	kg	Ecoinvent 3.3
Liquefied Petroleum Gas (LPG) (70 % propane, 30 % butane)	439	kg	Ecoinvent 3.3
Gasoline mix (premium) at the refinery	61.8	g	Ecoinvent 3.3
Aluminium extrusion profile mix	3.44	g	Ecoinvent 3.3
Diesel mix at the refinery	0.0588	g	Ecoinvent 3.3
Electricity grid mix	0.00236	MJ	Ecoinvent 3.3
Diesel mix at the refinery	72.9	g	Ecoinvent 3.3
Market for corrugated board boxes	101	kg	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Waste (solid) [Waste for disposal]	15.8	kg	Waste
Rigid plastic part	1000	kg	Intermediate Product
Bolt production			
Input	**Amount**	**Unit**	**Data source**
Electricity grid mix	0.351	MJ	Ecoinvent 3.3
Steel billet (28Mn6)	244	g	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Forged steel	1	kg	Intermediate Product
Metal pieces production			
Input	**Amount**	**Unit**	**Data source**
Steel welded pipe	16.9	kg	Experimental data
Carbon dioxide, liquid	0.163	g	Ecoinvent 3.3
Nitrogen, liquid	0.62	g	Ecoinvent 3.3
Steel cold rolled (St)	5.88	kg	Experimental data
Electricity grid mix	0.367	MJ	Ecoinvent 3.3
Lubricating oil	1.88	g	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Steel parts	14.2	kg	Intermediate Product
Frame production			
Input	**Amount**	**Unit**	**Data source**
Steel billet (St)	0.1	kg	Ecoinvent 3.3
carbon dioxide, liquid	7.27	g	Ecoinvent 3.3
Steel part	14.2	kg	experimental data
Argon	41.9	g	Ecoinvent 3.3
Electricity grid mix	52.9	MJ	Ecoinvent 3.3
Output	**Amount**	**Unit**	**Data source**
Steel frame	1	pcs.	Intermediate Product
Dirt sand	0.934	kg	Ecoinvent 3.3
Scooter assembly			
Input	**Amount**	**Unit**	**Data source**
Rigid plastic part	9	kg	Datasheet from the producer
Forged steel	0.318	kg	Intermediate Product, real-life measurement
Steel frame	1	pcs.	Intermediate Product, real-life measurement
Output	**Amount**	**Unit**	**Data source**
Scooter frame	1	pcs.	Product

construct the inventory for the benchmark (Table 5). The hardener was assumed to be ethylenediamine based on the most common epoxy resin hardener referenced by Eckert et al. [28] The geographical region for all processes in the LCA modeling is the European average market group. The electricity mix is from the Dutch electricity mix based on the location of the company manufacturing this biomonocoque. The wastes obtained throughout the production process are taken into account in the LCA as incinerated with energy recovery. The inert waste is landfilled.

3. Results and discussion

3.1. Interpretation of the results

The results obtained from the LCA are presented within this section as well as a detailed analysis of the observations. Section 3.1.1 exhibits the LCA results of the hemp fibre reinforcement value chain. Sections 3.1.2 and 3.1.3 present the LCA results of the two demonstrator production cases, namely the aircraft dashboard panel and the bioscooter monocoque respectively.

3.1.1. Hemp fibre reinforcement environmental impacts

The environmental impacts of the production of the woven hemp fibre reinforcement and two synthetic fibre reinforcements (woven glass fibre and carbon fibre woven fabrics) are shown in Figs. 3 and 4. Fig. 3 compares the GWP (in kg C O_2 eq.) of the production of the hemp fibre reinforcement based on the mass required to achieve equivalent specific E-modulus as the glass and carbon fibres as indicated in section 2.1.1. Fig. 4 compares the GWP of the production of the hemp fibre reinforcement based on the mass required to achieve equivalent specific tensile strength as the glass and carbon fibre reinforcements. According to Fig. 3, based on the mass required to achieve equivalent specific E-modulus, the production of the hemp preform reinforcement resulted in the GWP of 120.00 g C O_2 eq with a standard deviation of 20 g C O_2 eq. The glass fibre production resulted in a GWP of 140 g C O_2 eq with a standard deviation of 20 g C O_2 eq. This led to a difference of 14 % in terms of GWP. In the case of carbon fibre with equivalent specific E-modulus, the GWP results in 130 g C O_2 eq. with a standard deviation of 20 g C O_2 eq This is an 8 % difference when compared to the woven hemp fibre reinforcement [29,30].

The main cause of the observed differences between natural and synthetic fibre is associated with the accounted biogenic carbon that is taken up during the growth of the biomass, particularly in the case of hemp biomass [6,13,31]. This leads to negative emissions of carbon dioxide from the biosphere and therefore results in the reduction of the overall GWP score of the hemp fibre reinforcement production value chain. The production of glass fibre, which is fossil-based in nature, does not benefit from this biogenic carbon accounting, as the transformation processes of the fossil-based derivatives into glass fibres release new carbon dioxide into the atmosphere that was not initially in circulation but rather stored underground. The most impactful component in the inventory of the hemp preform production is the electricity consumption during the hemp preform production phase, namely the extraction of the fibres from the harvested hemp plants. Besides the accounting of the biogenic carbon, synthetic fibre production also involves more energy-intensive operations which contributed heavily to the values of the GWP [9,14,26]. This is particularly the case for carbon fibre production. If an areal density-based functional unit is used, for instance, in mass per area, the GWP warming potential of the carbon fibre can be 800 % higher. However, because the mechanical properties of the

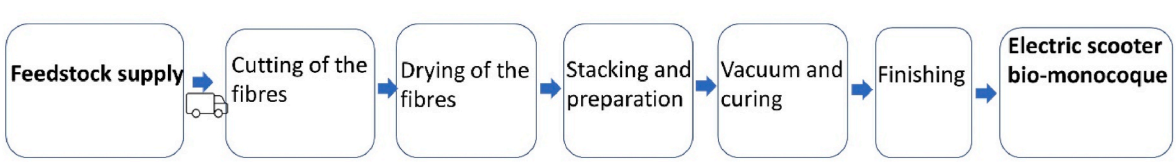

Fig. 2. Flowsheet of the electric scooter bio-monocoque production.

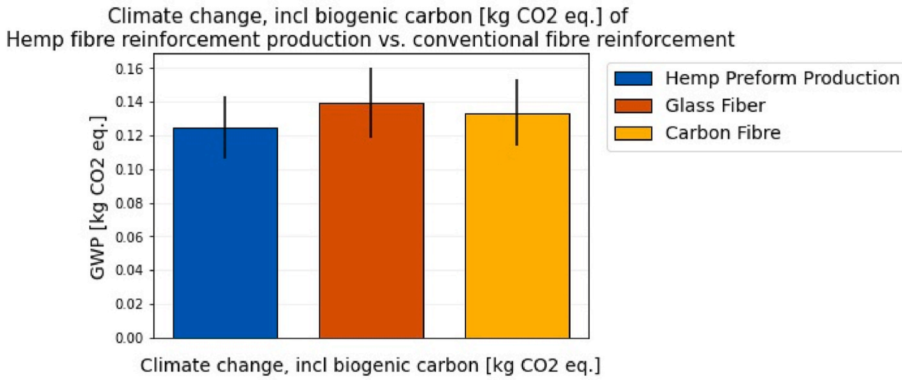

Fig. 3. GWP of the hemp fibre production VS conventional fibre reinforcement based on the mass required to achieve equivalent specific Young's-modulus.

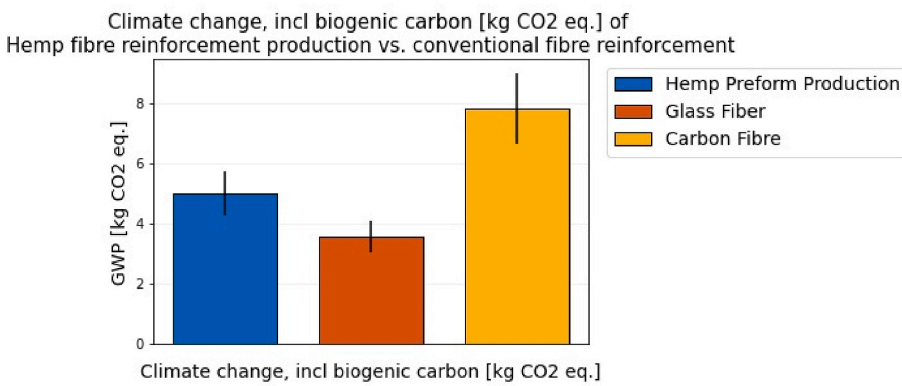

Fig. 4. GWP of the hemp fibre production VS conventional fibre reinforcement based on the mass required to achieve equivalent specific tensile strength.

natural fibre reinforcements are still much lower than for synthetic fibres, the differences in the GWP are then thus lower since more mass is required to achieve the same functionality as for glass or carbon fibre. But with this as the case, the investigation showed that the GWP for the natural fibre reinforcement is still lower than those of the synthetic fibres based on the mass required to achieve an equivalent specific E-modulus.

Fig. 4 illustrates the GWP of the different fibre reinforcements when the specific tensile strength is the same, hence, resulting in different masses needed to achieve the same functional unit. With that said, the GWP for hemp fibre reinforcement is calculated to be at 4.9 kg CO_2 eq with a standard deviation of 0.49 kg CO_2 eq. The GWP is also reported at 3.55 and 7.84 with a standard deviation of 0.355 kg and 0.784 kg CO_2 eq respectively for the glass and carbon fibre reinforcement respectively. The results showed that the GWP for the glass fibre is the lowest even when biogenic carbon is taken into account. This observation can be explained due to the fact that the tensile strength for the hemp fibre reinforcement is still much lower than those of the synthetic fibres, meaning that more mass unit is required in order to achieve the same tensile strength. Two points of interest are noted henceforth to further explain the differences observed here. Firstly, it should be noted that the production of the hemp fibre reinforcement is on a lab scale via a production route that has not been optimized yet. This is not the case for the environmental impact data obtained from the Ecoinvent databases for glass and carbon fibre as these values are obtained for optimized industrial processes. This means that the LCA should be iterated in the future in order to assess the impacts of industrial-scale hemp preform production to give a better comparison between all production routes. Secondly, it is also important to bear in mind that the mechanical properties, particularly the tensile strength, of natural fibres are undoubtedly lower than synthetic fibres. As such, further investigations are still being conducted in order to improve the mechanical performances of the hemp fibre preform which could lower the unit mass required and subsequently, decrease the GWP in the future.

Fig. 5 illustrates the normalized LCA results of the woven hemp fibre, the glass fibre, and carbon fibre reinforcement based on the mass required to achieve an equivalent specific E-modulus. Similarly, Fig. 6 illustrates the normalized LCA results based on the mass required to achieve equivalent specific tensile strength is achieved for woven hemp fibre, glass fibre, and carbon fibre reinforcements. Both of the results were normalized according to the midpoint hierarchic normalization factors from ReCiPe 2016. The normalization factors considered the amount of equivalent effects created per person in 2010 for the total world population. By performing this normalization, it is possible to additionally interpret the results in two main ways. Firstly, this allows the comparison of the different environmental impact categories with each other. Secondly, the normalized results demonstrate which of the impact categories deserve immediate attention for further process optimization and improvements. The normalized results showed that for fossil-based glass fibre production, impact categories such as human toxicity (cancer), photochemical ozone formation (both ecosystem and human health) as well as fossil depletion, among others, are the most impactful midpoint categories to the environment. This trend has been observed for both cases regardless of which mechanical properties were used as the basis for comparison. When investigating the normalized results for the hemp fibre reinforcements, all the aforementioned midpoint indicators appear to be lower for all impact categories. This highlights the importance and benefits of using natural fibre reinforcements, as opposed to fossil-based synthetic reinforcements. However, it should still be mentioned that when considering natural fibre reinforcements, impact categories such as land use, freshwater eutrophication, and marine eutrophication are higher than those of glass

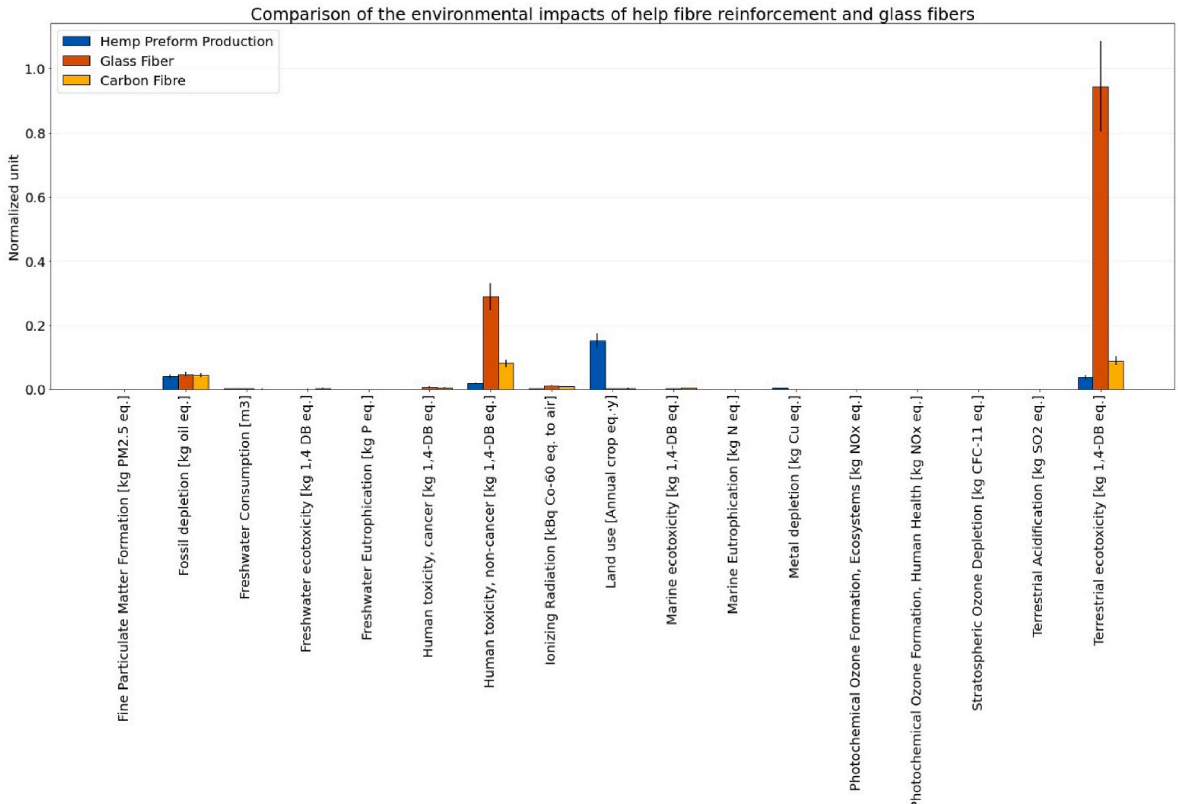

Fig. 5. Normalized environmental impact of the hemp fibre production VS conventional fibre reinforcement based on the mass required to achieve equivalent specific Young's-modulus.

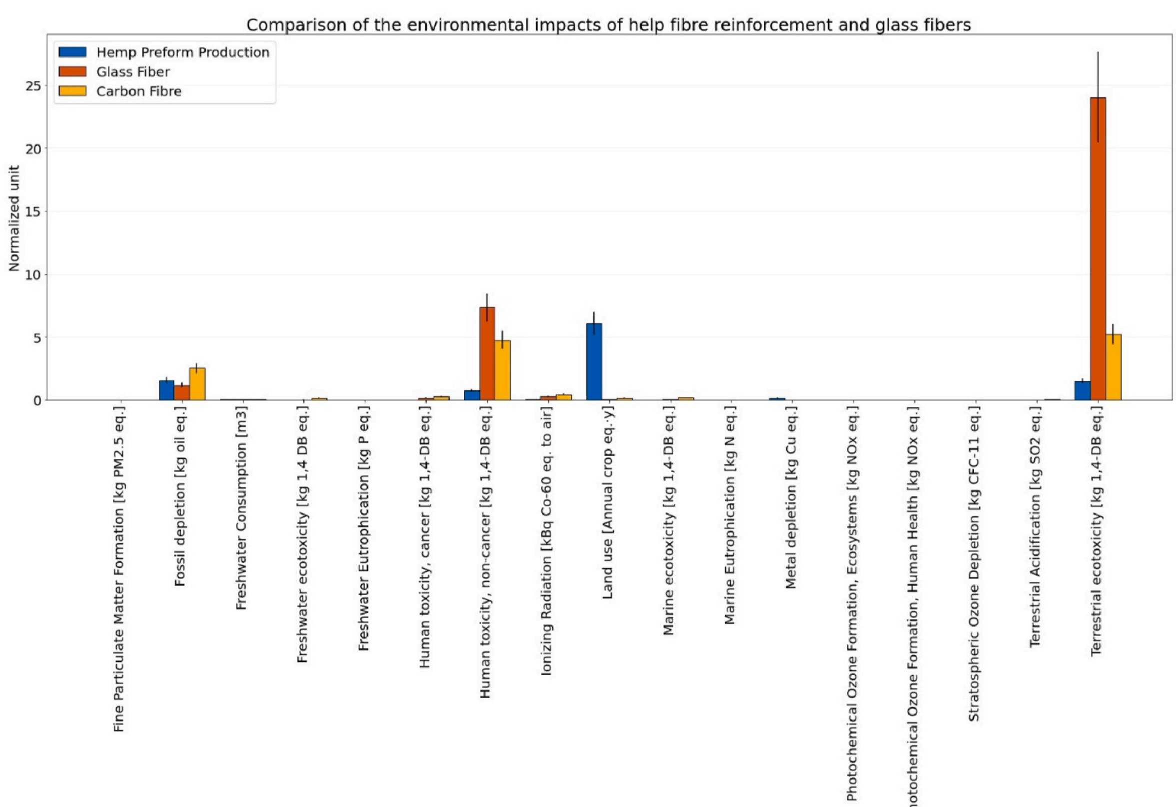

Fig. 6. Normalized environmental impact of the hemp fibre production VS conventional fibre reinforcement based on the mass required to achieve equivalent specific tensile strength.

fibres. These impact categories can often be associated with agricultural activities, such as the cultivation of biomass and the use of nitrogen or phosphorus components in fertilizers [24,26,32].

3.1.2. Case study application 1: aircraft dashboard panel environmental impacts

In order to demonstrate the environmental performance potential of hemp fibres versus synthetic fibres reinforcements, the first case study explores the possible application within the aviation industry (use of hemp fibres against carbon ones).

Fig. 7 depicts the global warming potential of the composite production phase for the electric aircraft dashboard panel demonstrator. Compared to the benchmark scenario of utilizing a carbon fibre-reinforced plastic (epoxy) panel with a mass of 0.792 kg, Fig. 7 demonstrates that using hemp fiber to construct one dashboard panel for an epoxy-based electric aircraft panel (approximately 1.53 kg of the sandwich panel) could reduce GWP by up to 68 %. More specifically, the GWP value of the production of the epoxy-hemp-based electric aircraft dashboard panel is equivalent to 23.7 kg C O_2 eq with a standard deviation of 2.37 kg C O_2 eq. The GWP value for the production of the carbon fibre reinforced epoxy composite is equivalent to approximately 74.4 kg C O_2 eq with a standard deviation of 0.744 kg C O_2 eq. Despite the need for a greater amount of material to fulfill undisclosed mechanical requirements, the hemp-based dashboard panel requires more mass than the carbon-based solution. However, the hemp fiber/epoxy composite exhibits a notable reduction in Global Warming Potential (GWP) compared to its carbon fiber/epoxy counterpart. This reduction can be primarily attributed to the environmental impacts associated with the production of hemp fiber. The production of carbon fibre is a very energy-intensive process that contributes largely to the higher GWP. On average, the cumulative energy demand for carbon fibre can be from 10 to 70 times the cumulative energy demand of hemp fibre production according to the literature [7,9,14]. In addition to this, as carbon fibre is a synthetic fibre with a fossil fuel source, carbon fibre does not benefit from biogenic carbon accounting and storage like natural fibres do. This also contributes to the reduction in the GWP for the hemp-based composite from the carbon fibre-based composite [11,23].

Fig. 8 presents the normalized data for each indicator's possible environmental impacts for all the evaluated production scenarios. The results were normalized using the midpoint hierarchic normalization factors from ReCiPe 2016, which took into account the number of equivalent effects created per person in 2010 for the total world population. This enables a thorough comparison of the various impact categories that were evaluated. Although human toxicity and cancer is the most significant environmental impact in the composite's manufacturing stage in all scenarios, according to Fig. 8, the bio-based panel can be less harmful in this impact category than the benchmark scenario. Besides the human toxicity, the cancer impact indicator, the photochemical ozone formation (both human health and ecosystem impacts), as well as the fossil depletion impact indicator, are among the most impactful indicators for the production of the electric aircraft dashboard panel for both the hemp-based and the carbon fibre-based epoxy reinforced composites. In all three indicators, hemp-based composite production generated lower impacts than carbon fibre-based composite manufacturing. In addition to this, the hemp-based dashboard panels outperformed the carbon fiber-epoxy composite benchmark in all remaining environmental impact indicators.

3.1.3. Case study application 2: scooter monocoque environmental impacts

Fig. 9 shows the global warming potential of the composite manufacturing phase for the bio-monocoque panel demonstrator. According to this figure, the GWP of manufacturing the epoxy-based bio-monocoque scooter frame is equivalent to 62.8 kg C O_2 eq with a standard deviation of 6.28 kg C O_2 eq. This value is lower than the C O_2 equivalent of the benchmark steel frame scooter with ABS bodywork, which has a GWP of 100 kg C O_2 eq. As is the case with the aircraft dashboard panel, the lower GWP can be associated with the possibility of accounting for the biogenic carbon flow for the biomass that is a part of the hemp fibre-based epoxy bio-monocoque. Since the steel frame consists of steel parts and ABS polymer parts, there is no biomass present within the steel frame scooter. Therefore, the combination of the lack of biogenic carbon accounting as well as the higher energy consumption, the steel frame scooter resulted in a higher GWP value of about 37 % than the GWP value of the hemp fibre reinforced epoxy bio-monocoque.

Fig. 10 illustrates the normalized results of the environmental impact indicators using the midpoint hierarchic normalization factors from ReCiPe 2016, which considered the number of equivalent impacts created per person in 2010 for the total world population for each environmental impact indicator. This allows for a comparison of the different impact categories. Based on the obtained normalized results, impact categories such as terrestrial ecotoxicity, climate change, and fossil depletion are among the most impactful categories accordingly. For all three impact categories, the steel frame scooter with ABS bodywork scored higher than the bio-monocoque scooter. This observation can also be made for most of the assessed environmental impact indicators where the steel frame with ABS bodywork is more impactful than the bio-monocoque scooter. However, impact categories related to agricultural activities such as land use and freshwater consumption are shown to be higher for the bio-monocoque scooter than for the steel frame with ABS bodyworks. This is to be expected, based on the cultivation and growth of biomass [8]. The bio-monocoque scooter production also resulted in slightly higher impacts related to human toxicity, and non-cancer than for the steel frame scooter with ABS bodywork. The impacts related to human toxicity can be mostly associated with the use of resin, particularly epoxy resin and ABS resin, in the production of both the bio-monocoque and steel frames with ABS body works respectively.

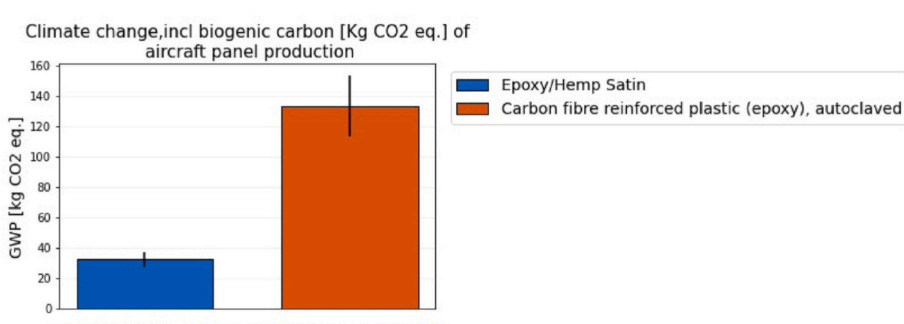

Fig. 7. GWP of aircraft panel production.

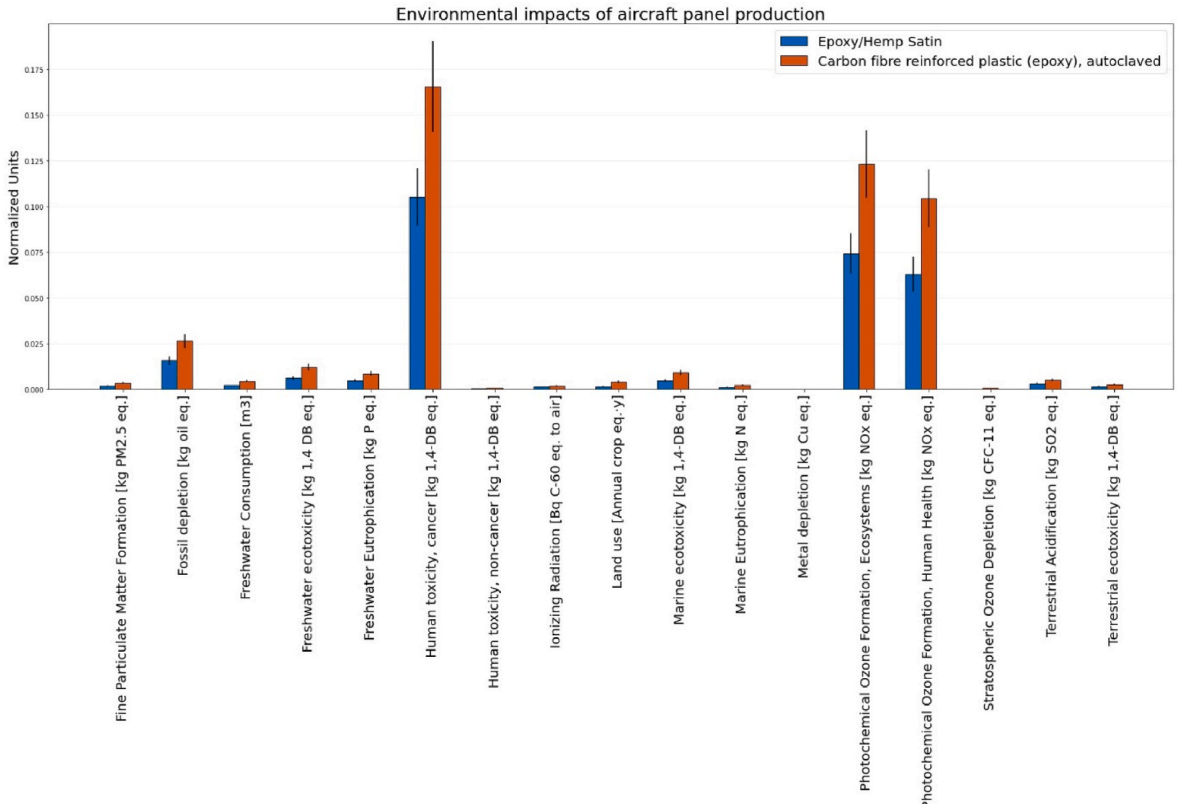

Fig. 8. Environmental impacts of aircraft panel production.

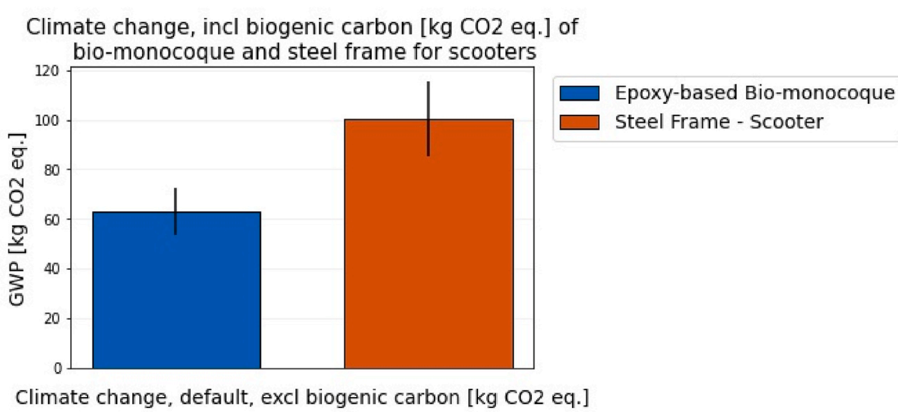

Fig. 9. GWP of the bio-scooter and the steel frame scooter production.

3.2. Comparison of the case study results with the state-of-the-art in natural fibre and synthetic fibre reinforcements

Based on the previous section 3.1, the environmental impacts of the hemp fibre reinforcement and its two application case studies were presented and discussed. In this section, the obtained results are subsequently compared with the state-of-the-art studies. To this end, the section is divided into three parts consisting of the discussion of the hemp fibre reinforcement and the latest advancements in the bio-composite applications in the aerospace and two-wheel drive industries.

Firstly, the obtained environmental impact results presented in this study are aligned with other state-of-the-art studies that have performed the LCA with the same scope and functional unit. For instance, the study of La Rosa et al. [33] reported that the production of 1 kg of hemp mat resulted in less GWP and cumulative energy demand (CED), among other impact categories than the production of 1 kg of glass fibre. Specifically, the study reported a GWP of 2.95 kg CO_2 eq. for the production of 1 kg glass fibres as opposed to a GWP of 0.531 kg CO_2 eq. for the production of 1 kg of the hemp mat. For clarity, it should be noted here that a mat often consists of finely chopped hemp strands that are oriented randomly in all directions, however, a woven fabric is often oriented in normally two directions. Similarly, the cumulative energy demand (CED) was also reported at 51.3 MJ for glass fibres mats and 8.89 MJ eq. for hemp mats. The only impact category that scored higher for hemp fibre production was the land occupation at 1.54 m^2, while this value was 0.0692 m^2 for glass fibre production. This outcome was to be expected and was aligned with the results from the present study, due to the agricultural activities associated with the production of hemp natural fibres. To add dimension to the comparison, the value for the CED of carbon fibre production is reported at 350.2 MJ per kg according to the

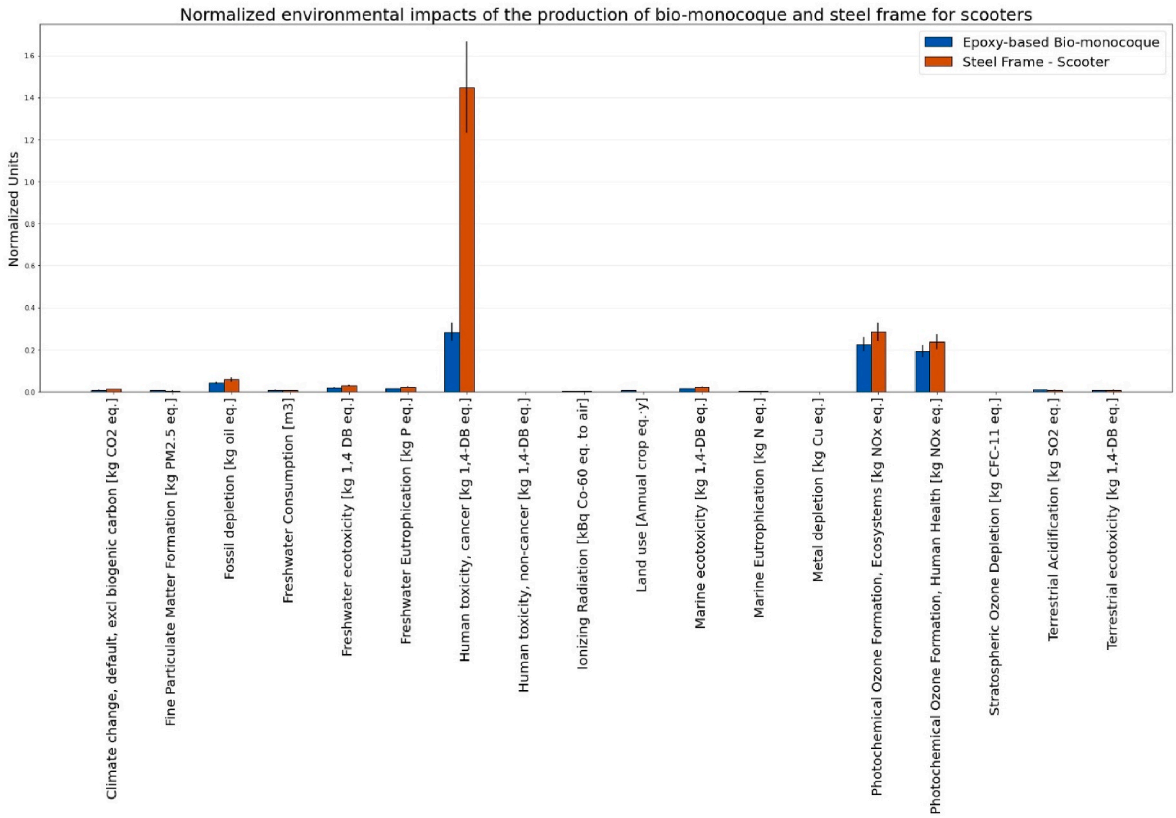

Fig. 10. Environmental impacts of bio-monocoque queue panel production VS steel frame production.

Japan Carbon Fiber Manufacturers Association [34]. To illustrate this, Duflou et al. [9] also reiterated the findings of this study about greenhouse gas emissions (GHG) and CED for the production of different synthetic and natural fibres. The production of 1 kg of glass fibres prior to weaving was reported to have a CED value of 45 MJ and a GHG of 2.6 kg CO_2 eq. The production of 1 kg of the hemp fibre (without irrigation) prior to weaving was reported to have a CED value ranging from 6.8 to 13.2 MJ and a GHG of 1.6 kg CO_2 eq, instead. In another review by Shazad et al. [17], the environmental impacts of the production of 1 kg of hemp and glass fibres were also presented and compared. The review indicated that the production of 1 kg of glass and hemp fibres resulted in carbon dioxide emissions of 20.4 kg CO_2 eq. and 0.64 kg CO_2 eq., respectively. Other emissions such as SO_X and NO_X were also shown to be higher for glass fibre production than hemp fibre production. The energy demand in MJ for glass fibre production was also reported at 48.3 and 3.4 for hemp fibre production. However, the review did not include other parameters related to agricultural activities such as land use, phosphates, or nitrogen emissions, which could all provide a holistic insight into the environmental impacts related to the production of natural fibres. Based on the presentation of the results in section 3.1 and other state-of-the-art studies, the potential for natural fibres to replace synthetic fibres can be highlighted, especially for concerns about the reduction of the energy requirements and the GWP. However, the environmental impact categories related to agricultural activities should also be considered to derive the most holistic overview of the usage of natural fibres.

The obtained environmental impacts of the aircraft dashboard panel are now compared to the aircraft panels reported in the literature, with a particular focus on the comparison between the natural fibre reinforced epoxy composite and the carbon fibre reinforced epoxy composites. As previously mentioned in this text (as well as being re-iterated in different publications), the production of fossil-based carbon fibres is an order of magnitude higher in terms of energy consumption. This in turn often led to higher GWP. The review study of Bachman et al. [35] investigated 14 LCA studies focusing on the replacement of synthetic fibres with natural fibre reinforcements (even if none of the studies focused specifically on composites for aerospace applications). The review also highlighted the possibility for natural fibre reinforcements to perform better in terms of the GWP due mainly to the reduction in the energy demand for natural fibre production, especially in the case of replacements of carbon fibres. However, the review also drew attention to the specific nature and high standards of requirements for the aerospace industry, meaning that the current LCA data and the inventory available on databases may be underestimating the actual mechanical grade of the materials which could differ from the common grade materials for other applications. In line with the finding of this paper, an important environmental hotspot for natural fibre-reinforced epoxy composite lies in the epoxy resin matrix, as proposed by the review paper. To this end, the substitution with bio-based resin could help to reduce the environmental impacts of the resin matrix further. Similarly, the study of Vidal et al. [36] investigated the environmental impacts of the production of aircraft interior panels, particularly the conventional glass fiber reinforced composite with potentially sustainable flax fibre reinforced composites (biopolymer, polypropylene, and polylactic acid) per 1 m^2. The GWP for all flax fibre-reinforced composites (for all resin matrix types) ranged from 6 to 14.5 kg CO_2 eq. while the GWP value was reported at over 20 kg CO_2 eq. for the glass fibre reinforced phenolic resin composite. However, it should be mentioned here that the current unit of comparison across the different studies is surface-based. This choice could be questioned and discussed to propose a more relevant unit of comparison such as a mechanical performance-based unit related to the mass required to achieve the same mechanical performance. To this end, many LCA studies have indicated the potential reduction of the GWP for the replacement of synthetic fibre with natural fibre reinforcements. Additionally, the replacement of the matrix resin with a bio-based version could also reduce the environmental impacts of the entire composite structure. However, attention must be placed to ensure the high-end and specific mechanical requirements for using these composites in the aerospace industry. Therefore, this highlights the importance of performing LCAs at various stages of aircraft panel production in order to improve the quality of the LCA results.

The environmental impacts of the bioscooter monocoque are here compared against those of biocomposites produced for automotive applications and reported in the literature. As the state-of-the-art literature with an application specific to the biocomposites for scooters or two-wheel vehicles is virtually non-existent, the choice was made to compare the obtained results with those composites of the automotive applications with similar structures. Firstly, studies by Wötzel et al. [19] demonstrated that the replacement of the ABS door panel in the automobile with hemp fibre reinforced (at 66 wt% fibre content) epoxy panel could provide, in the manufacturing phase, energy savings by up to 45 %. Additionally, the greenhouse gas emissions were estimated to be reduced by 12 % with the replacement of hemp fibre reinforced composites and up to 28 % when biogenic carbon is taken into account. In addition to this, studies by Müssig et al. [37] and Schmehl [22] also reported similar findings, in which the replacement of the glass fibre-based polyester exterior panels for buses with hemp fibre-based triglycerides and polycarbon acid anhydrides polymer matrices reduced energy requirements by 26 %. The replacement also resulted in a greenhouse gas reduction of up to 41 % in the production phase and up to 74 % when the biogenic carbon was also considered. Most LCA studies estimated that the reduction in greenhouse gas emissions would not only be during manufacturing but also during the operational use, as the adoption of natural fibers, and reinforced composites can often lead to the reduction of the mass of the entire composite structure. Therefore, fuel consumption could be reduced during usage and decrease overall greenhouse gas emissions. In line with other publications, the results reported within this study also highlighted the benefits in terms of greenhouse gas emissions when natural fibre composites are used to replace synthetic fibre structures in automotive/two-wheel drive applications. Similarly to the case of the aircraft dashboard panel, it is of high importance to perform the LCA of the bio-monocoque structure at different technology readiness levels, in order to improve the quality of the LCA results based on the scale-up data inventory and the possibility of expanding the scope of the LCA to include the use phase. To this end, it should be possible to visualize the environmental benefits and trade-offs holistically which could subsequently lead to the design of an optimal value chain for natural fibre reinforced composites for different applications.

3.3. *Current limitations and outlook for future studies*

The current study does have some limitations as it is often the case faced by LCA practitioners, particularly concerning data availability. Further improvements on the current LCA studies could include the application of a regionalized LCA with region-specific data, the expansion of the impact indicators associated with the agricultural activities, and the expansion of the scope of the study to cover the life cycle of the fibres or composites from cradle to grave. Doing so could potentially improve the applicability, specificity, and interpretation of the obtained LCA results. Consequently, the additional information generated could aid in the further understanding of the potential to substitute synthetic fibre with natural fibre reinforcements.

Because life cycle assessments are regionally dependent, the scope of the LCA should encompass a regional context specification [38]. The availability of resources and supply chains are affected by the location of fibre cultivation. Land and water territories are valuable resources that vary greatly from country to country. Furthermore, the percentage of land and water that would be used to grow fibers varies greatly. The environmental impact of the manufacturing of fibre can be influenced by regional differences in terms of resource extraction and market value of the raw materials. The regional electrical mix, for example, has a significant influence on environmental impacts. Another example is transportation factors in LCA assessments of bio-based systems which are exceedingly varied. Transportation was determined to be one of the most significant factors in the total environmental impact of bio-based systems in various research. As a result, a definition of ideal production sites for cultivating the fibres needs to be set out by taking into account a variety of technology pathways and environmental impacts.

Further studies could consider water stress indicators within the life cycle impact. Water consumption for the production of natural fibres must be evaluated in the context of water-resource competition among other applications, because demand for freshwater resources is rapidly expanding in numerous economic sectors, including energy generation. The implementation of fibre cultivation facilities should intentionally target locations with low water stress impacts for sustainable fibres production.

Another aspect to consider in future studies is to expand the scope of the LCA to include usage (operational phase) and end-of-life or in other words, to set the scope to cover the life cycle from cradle to grave. The reduction in the mass can possibly lead to lower fuel consumption during the use of the product. Hence, it could be of great interest to further characterize the produced bio-composites and estimate the potential mass reduction, which could result in lower fuel consumption. This in turn would lead to lower environmental impacts throughout the life cycle. Moreover, the inclusion of the end-of-life study could also help clarify and explore the disposal possibilities of the composite. Subsequently, it should also be possible to derive a disposal strategy with the lowest environmental footprint. The current limitations to this expansion in scope are related to the lack of empirical data that could be used to perform the LCA study. Therefore, this early-stage LCA is limited as an interpretation of the full life cycle of the system under study and should be repeated at different stages of the technology readiness level of the two demonstrator applications when more inventory data is available.

Finally, when referring to the lab scale inventory that is assessed in this current LCA study, upscaling of the inventory should also be performed, followed by doing a prospective LCA. By performing prospective LCA (pLCA), the LCA of the future upscaled scenarios of the natural fibre preform production could be realized and compared with the industrial-scale environmental impacts of the glass and carbon fibre reinforcements at the same scale.

4. Conclusion

With rising demands in terms of manufacturing of consumer goods, the possibility of shifting the dependency from synthetic fiber reinforcements often derived from fossil-based sources, to environmentally sustainable natural fibre reinforcements becomes even more paramount. This study, therefore, aims to investigate and propose a potentially environmentally viable value chain for the production of natural fibre reinforcements, particularly based on hemp fibres. In addition to this, the study also explored two potential application cases: one related to hemp fibre reinforced epoxy composites for an aerospace application, and the other on a hemp-based bio-monocoque for an electric scooter. The goal of the two case studies is to demonstrate potentially environmentally sustainable value chains, in which natural fibre reinforcements can be used to replace the conventional structure.

Using a life cycle assessment, this study presents a hemp fibre reinforcement production value chain that could have a lower environmental footprint (especially in terms of GWP) than common synthetic fibre reinforcement productions, like glass or carbon fibres when the functional unit of the mass unit required to achieve equivalent specific E-modulus is used. However, when the functional unit of the mass unit required to achieve the same specific tensile strength is used, the glass fibre reinforcement results in the lowest GWP. Nonetheless, the LCA should be reiterated once the optimization of the preform production process is conducted as well as the investigation on the mechanical properties improvement is finalized. The first case study demonstrates an application case where the hemp fibre reinforced epoxy aircraft dashboard panel has a global lower environmental and GWP footprint than the analogous carbon fibre reinforced epoxy panel. Similarly, the second case study also shows lower environmental impacts when the hemp fibre-based bio-monocoque replaces the steel frame with ABS bodyworks for electric scooters. However, the LCA results also highlight possible areas of improvement related to agricultural activities-based environmental impacts indicators such as land use, freshwater consumption, and eutrophication, which are often higher for natural fibres than for synthetic fibre reinforcements.

Future studies in these topics should incorporate regional LCA, which could provide more specific LCA results better adapted for regional specifications. Moreover, when more characterization data of both the hemp reinforcements and the application demonstrators are available, the functional unit in the LCA should be adapted toward the mechanical properties, and the scope of the LCA should be further expanded to include usage and end-of-life scenarios. Finally, in addition to this early-stage LCA, the environmental assessment should be performed at every stage of the technology readiness level for both the hemp fibre reinforcements and the two demonstrators to quantify in a more exhaustive and accurate manner the environmental footprint. The use of prospective LCA to derive future industrial-scale scenarios of natural fibre preform production could also provide additional insights and better comparability with the synthetic fibre benchmarks which are already on an industrial scale. Regardless of the limitations within this LCA study, natural fibre reinforcements have been shown here (and in other studies) to be a potentially environmentally sustainable alternative to synthetic fibres and could indeed help mitigating climate change depending on the application that the natural fibres can fulfill.

Credit authorship contribution statement

Hanie Zarafshani: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. Ponnapat Watjanatepin: Resources, Writing – review & editing. Mark Lepelaar: Providing the raw data for building the bioscooter composite, Writing – reviewing & editing. Jens Verbruggen: Providing the raw data for building the bioscooter composite, Writing – reviewing & editing. Pierre Ouagne: Providing the raw data for building the hemp preform, Writing – review & editing. Rosario De Luca: Providing the raw data for building the airplane dashboard panel, Writing – review, and editing.Qinyu Li: Providing the raw data for building the airplane dashboard panel, Writing – reviewing & editing.Fabrizio Scarpa: Providing the raw data for building the airplane dashboard panel, Writing – review, and editing. Vincent Placet: Writing – review & editing, Supervision, Project administration, Funding acquisition. Karel Van Acker: Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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